ANALYSIS OF MULTIPLE SITE DAMAGE WITH IMPLICATIONS FOR NONDESTRUCTIVE EVALUATION

Kimberley Buhler
Warner Robins Air Logistics Center
Robins AFB, GA 31098

Alten F. Grandt, Jr.
School of Aeronautics and Astronautics, Purdue University
W. Lafayette, IN 47907-1282

INTRODUCTION

Multiple-Site Damage (MSD) in aging aircraft has motivated analysis of the fatigue life of a panel containing a row of cracked holes [1-3]. Given the initial MSD configuration and loading conditions, individual cracks are grown incrementally until link-up or the panel failes. First, stress intensity factors are calculated for all cracks. One crack tip is then assumed to advance a small amount, and the cycles for this increment of growth are calculated. The remaining cracks are then grown a distance corresponding to this cyclic interval by employing a fatigue crack growth model to relate the cyclic stress intensity factor and fatigue crack growth rate. After each incremental growth the current crack geometry is compared to one of several failure criteria [3] to determine whether the panel fails. For holes which are initially uncracked, cumulative damage is summed at these locations in conjunction with a Neuber notch analysis. When this strain-life analysis determines that "crack initiation" has occurred at a given hole, crack growth calculations continue at that location, and the routine is repeated until the failure criterion is satisfied.

Experiments were conducted with nine inch wide 2024-T3 aluminum panels to verify the analysis [1-3]. The 0.09 inch thick specimens contained a single row of 8 to 11 open holes with a 0.16 inch diameter. All specimens were precracked in fatigue. Some contained large lead cracks, and all had small radial MSD cracks (on the order of 0.05 to 0.10 inches long) at two or more of the remaining holes. These specimens were cycled under constant amplitude loading, and the formation, growth, coalescence, and final failure was recorded and compared with results of the LEFM based numerical analysis. Figure 1 summarizes measured and predicted life for the 12 tests conducted. A separate set of experiments [3] with similar precracked MSD specimens indicated that the Swift [4] ligament yield criterion gave a good estimate of residual strength for those test specimens. Further details of the test results and analysis procedure are provided in Refs. 1-3.

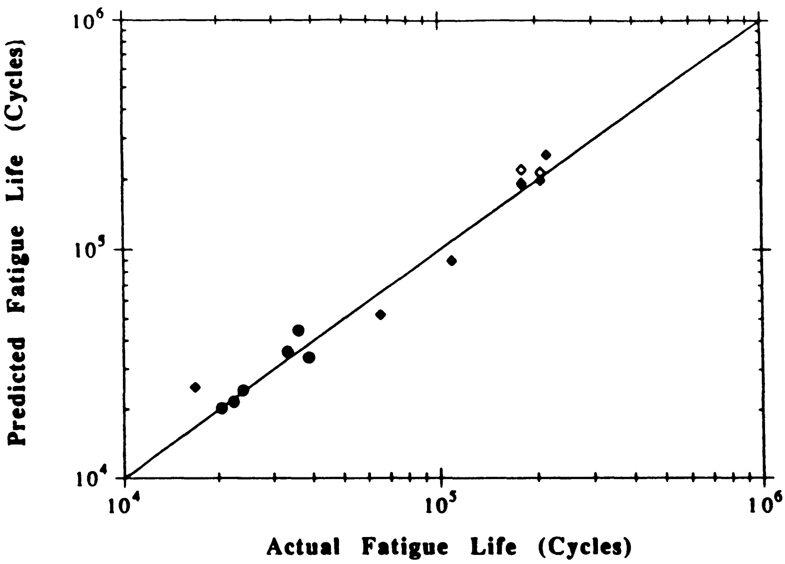
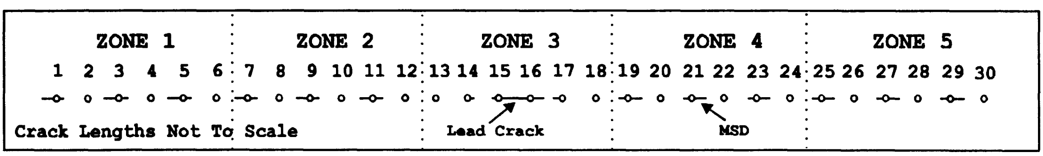
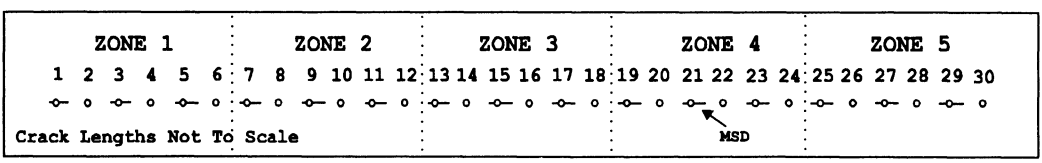


Figure 1. Predicted versus measured fatigue lives for 12 MSD fatigue tests.



Example of a cracked panel containing MSD and a lead crack.



Example of a cracked panel containing MSD at every alternate hole.

Figure 2. Typical starting configurations considered in numeric study.

PARAMETRIC STUDY OF A WIDE PANEL WITH MSD

Having established confidence in the ability to analyze multiple site damage, this paper describes a parametric study of various MSD scenarios in an unstiffened panel. As shown in Fig. 2, a 31.0 inch wide panel containing 30, 3/16 inch diameter holes was selected as the test model. Two basic crack configurations were considered: panels containing a 'lead' crack *and* MSD cracks growing from other holes, and panels containing combinations of MSD cracks *without* a lead crack. The main goal here was to determine how various MSD scenarios affect the life of a large panel, and to determine trends in crack growth which might guide inspection requirements associated with the MSD problem.

Two radial hole crack sizes were selected to represent typical MSD fatigue cracks: 0.05 inches and 0.1 inches. Panels were divided into five zones of six holes (Fig. 2) to study various crack combinations. Three lead crack configurations were located in the central zone shown Fig. 3. For each lead crack type, various combinations of MSD cracks were placed in the other zones. Symmetrically and nonsymmetrically placed cracks were studied with three maximum applied cyclic loads: 10.0, 12.5 and 15.0 ksi. A total of 135 cases were considered in the parametric study; further details of the variables are given in Ref. 5.

DISCUSSION OF RESULTS

Typical Crack Growth Trends

Tables 1 and 2 present total panel lives for several specific cases considered (individual crack growth curves are given in Ref. 5). Typically, the crack growth scenerio with lead crack cases involved rapid growth of the large flaw, followed by coalescence with

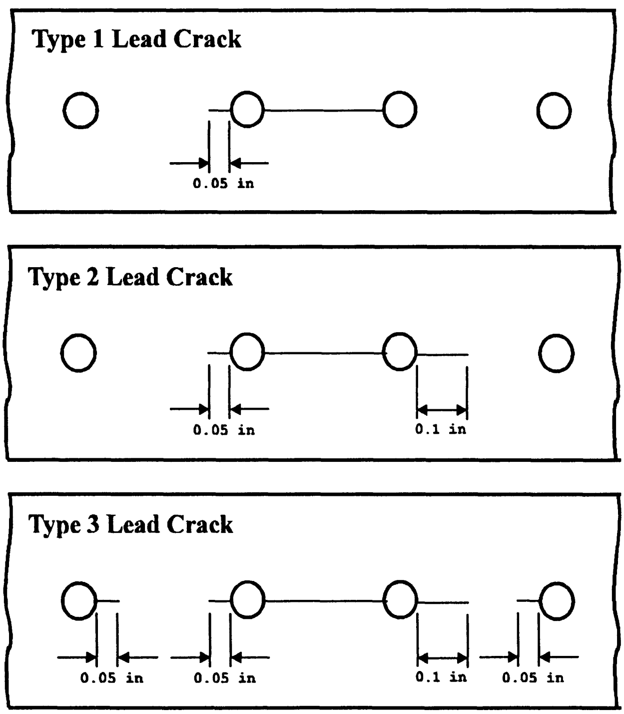


Figure 3. Details of the lead crack configurations.

MSD cracks in adjacent holes. If the leadcrack grew into an uncracked hole, it would stop for a period of cycles. The "initiation" life required to develop a new crack tip at the opposite side of the hole was then computed by a Neuber notch analysis [1], and the lead crack would continue to grow. This process continued with the lead crack linking with other MSD cracks, until the panel failed.

For panels without initial lead cracks, the small MSD cracks would grow until linking with adjacent holes or cracks to form a lead crack. The resulting cracks grow and link with the adjacent holes as before, and the panel soon fails. These failure patterns suggest that regardless of the initial crack configuration, crack growth and coalescence will tend to result in a much larger crack, which will control the failure of the panel as it extends through other holes. Additionally, the number of cycles required to fail the panel after the dominant crack has reached some critical length is a small portion of the total panel life, and is effected by the initiation times of the initially uncracked holes. Based on this pattern, the life of the panel is dependent on how long it takes for a particular crack configuration to generate the larger critical crack. The next sections discuss the effects of the various initial crack configurations and applied loads.

Effects of Different Crack Configurations on Panels Containing a Lead Crack

A series of predictions were made with lead cracked panels which contained varying numbers of cracked holes. The number of cracked holes remotely located from the lead crack ranged from 0 to 12, and was selected to simulate the initial onset of a MSD scenario. Predictions were made for three different cyclic load levels (10, 12.5, and 15.0 ksi) for each crack configuration. Table 1 indicates that the type of lead crack and magnitude of applied load have a great effect on the total panel life. For the 10.0 ksi applied load case, for example, the panel with the type 1 lead crack and 8 other cracked holes (MSD334) had a total life of 73,021 cycles. By comparison, the same case with the type 2 lead crack (MSD335) had a life of 40,921 cycles, which is approximately 40 percent less than the life of the type 1 case. Similarly, the same case with the type 3 lead crack (MSD336) had a total life of 30,616 cycles, which is approximately 25 percent less than the type 2 life.

The magnitude of the applied loading also has a large effect on the panel lives. For example the life of the panel containing the type 1 lead crack with 8 other cracked holes (MSD334), ranged from 73,021 cycles for 10 ksi cyclic stress, to 7,054 cycles for the 15 ksi load. Similarly the type 3 lead crack case (MSD336) ranged from 30,616 cycles to 2,988 cycles. The fatigue life for the panel loaded at 15 ksi was approximately 10 percent of the life when loaded at 10 ksi.

Table 1 also indicates that moving the same number of cracked holes remote from the lead crack to various zones has a negligible effect on panel life. For example moving three remotely cracked holes to different zones in the type 1 lead crack panel (MSD316, MSD322), causes the total life to vary from 91,291 cycles to 91,281 cycles. This is due to the dominance of the lead crack in controlling panel life. In summary the lives of these panels are strongly controlled by the type of lead crack, the location of the other MSD relative to the lead crack, and the magnitude of the applied loading.

Effects of Different Crack Configurations on Panels Without a Lead Crack

Similar crack growth patterns were found for panels without lead cracks. The initial MSD cracks grow and coalesce to form a large central crack which rapidly extends to panel failure. Predictions were made for increasing numbers of cracked holes. In some cases the cracked holes were clustered together, while in others they were separated by uncracked holes. Additionally, predictions were made for a cluster of six initially cracked holes which were moved about the panel. Some specific results for these cases are listed in Table 2.

These results show that panel lives are strongly influenced by the number of cracked holes clustered together. Referring to Table 2, the results from case numbers MSD406 and MSD402 show a considerable difference in panel lives when the cracked holes are adjacent rather than being separated by an uncracked hole. For example, if a total of 15 cracked holes are initially clustered together in groups of three, the panel life was 50,336 cycles. When the same number of holes are separated by an uncracked hole, the panel life increased to 79,407 cycles, which is 58% greater than for the clustered case.

Figure 4 summarizes total panel life versus the number of clustered holes in these panels. Again, note the large reduction in life as the applied loading increases. Also note that for a particular applied load there appears to be a threshold for the sensitivity of life to the number of cracked holes which are clustered together. For a load of 10.0 ksi, for example, the panel life is about the same when there are clusters of 4 and 6 holes. For a load level of 12.5 ksi Fig. 4 shows that the panel life is insensitive to additional MSD once three holes are cracked, while for a load of 15.0 ksi a two cracked hole cluster is the critical minimum.

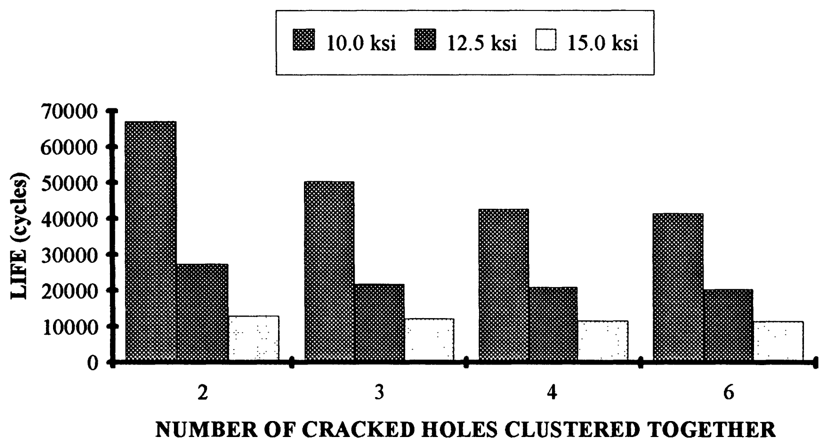
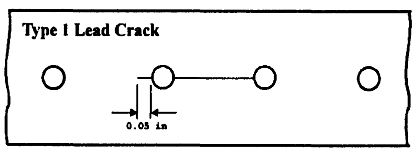
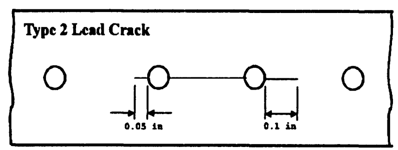


Figure 4. Total life versus number of clustered holes for panels containing no initial lead crack.

Table 1: Highlights of Specific Results For Panels Containing Lead Cracks and MSD

CRACK CONFIGURATION								PANEL LIFE (CYCLES)		
LEAD CRACK TYPE	TEST REFER. NO.	TOTAL NO. OTHER CRACK HOLES	ZONE 1 NO. OF CRACK HOLES	ZONE 2 NO. OF CRACK HOLES	ZONE 3 NO. OF CRACK HOLES	ZONE 4 NO. OF CRACK HOLES	ZONE 5 NO. OF CRACK HOLES	LOAD: 10.0 KSI	LOAD: 12.5 KSI	LOAD: 15.0 KSI
1	MSD316	3	1	1	2	1	-	91,291	29,192	8,393
1	MSD322	3	1	1	2	-	1	91,281	-	-
1	MSD325	4	1	1	2	1	1	86,306	28,088	8,060
1	MSD331	4	-	-	6	-	-	32,414	10,034	3,082
1	MSD334	8	2	2	2	2	2	73,021	24,437	7,054
1	MSD340	3	-	3	2	-	-	55,821	23,606	8,438
1	MSD343	3	-	2	3	-	-	52,721	22,911	8,106
2	MSD326	4	1	1	2	1	1	45,578	13,133	3,241
2	MSD332	4	-	-	6	-	-	15,250	5,358	1,270
2	MSD335	8	2	2	2	2	2	40,921	12,051	2,988
3	MSD336	8	2	2	4	2	2	30,616	9,020	2,360





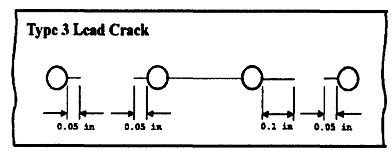
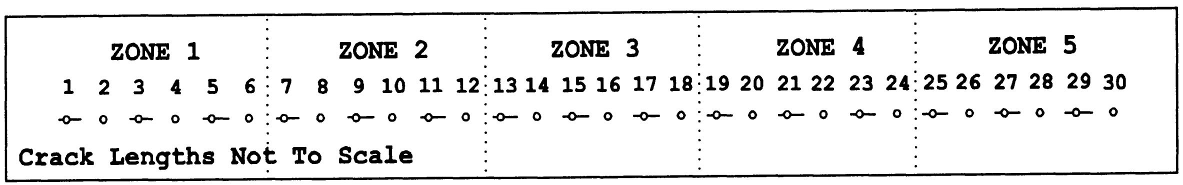


Table 2. Highlights of Specific Results For Panels Containing MSD Without a Lead Crack

CRACK CONFIGURATION								PANEL LIFE (CYCLES)		
TEST REFER. NO.	TOTAL NO. OF CRACK HOLES	ZONE CRACK CONFIG	ZONE 1 NO. OF CRACK HOLES	ZONE 2 NO. OF CRACK HOLES	ZONE 3 NO. OF CRACK HOLES	ZONE 4 NO. OF CRACK HOLES	ZONE 5 NO. OF CRACK HOLES	LOAD: 10.0 KSI	LOAD: 12.5 KSI	LOAD: 15.0 KSI
MSD401	30	GROUP	6	6	6	6	6	41,596	20,394	11,478
MSD406	15	GROUP	3	3	3	3	3	50,336	21,797	12,237
MSD402	15	APART	3	3	3	3	3	79,407	37,992	20,668
MSD405	10	GROUP	2	2	2	2	2	67,010	27,369	12,981
MSD403	10	ARART	2	2	2	2	2	97,727	40,146	20,956
MSD404	5	APART	1	1	1	1	1	124,025	54,066	27,986

Note: GROUP = clusters of initially cracked hole grouped together,
APART = cracked holes initially separated by one or more uncracked holes.



Example: MSD402 - Cracked holes separated by uncracked holes.

CONCLUSIONS

This paper describes an analysis to predict the fatigue crack growth, coalescence, and ultimate failure of a panel with a row of open holes containing MSD. The analysis has been verified by a series of tests which agreed well with the predictions. The program was then used to study the fatigue behavior of a wide panel containing many open holes and various crack configurations. Several conclusions were drawn from the parametric study.

a. Lead cracks grow and coalesce with MSD cracks leading to panel failure. Large cracks which grow into initially uncracked holes are delayed, but eventually continue growing as a new crack tip "initiates" on the opposite side of the hole.

b. The lead crack type has a strong effect on the fatigue life, and MSD located immediately adjacent a lead crack presents the most damaging crack configuration.

c. The maximum applied cyclic stress greatly effects the total panel fatigue life.

d. For panels without lead cracks, the MSD cracks coalesce to develop a dominant crack, and then a similar fatigue crack growth pattern as for the lead crack case applies.

e. Clusters of cracked holes not separated by uncracked holes present the most damaging crack configuration, and should be the focus of NDE programs.

REFERENCES

1. E.J. Moukawsher, "Fatigue Life and Residual Strength of Panels With Multiple Site Damage", M.S. Thesis, School of Aeronautics and Astronautics, Purdue University, May 1993.
2. E. J. Moukawsher, A. F. Grandt, Jr., and M. A. Neussl, "A Fatigue Analysis of Panels With Multiple Site Damage, *1992 USAF Structural Integrity Program Conference,* San Antonio, Texas, December 1-3, 1992
3. E. J. Moukawsher, A. F. Grandt, Jr. and M. A. Neussl, "Analysis of Panels with Multiple Site Damage," AIAA Paper No. 94-1459, *AIAA SDM Conference,* Hilton Head, SC, April 18-21, 1994.
4. T. Swift, "Effect of MSD on Residual Strength", from a presentation given at the U.S. Air Force Symposium on Multi-Site Damage, February 1992.
5. K. Buhler, "A Study of Fatigue Crack Growth of Panels Containing Multiple Site Damage," M.S. Thesis, School of Aeronautics and Astronautics, Purdue University, December 1993.